Ultra Low Cost Launch Vehicles A Stimulus For Turning Around the Dramatic Decline of the U.S. Aerospace Industry

Presented at the NSSTC Science Colloquium

27 January 2006

Robert L. Sackheim
Assistant Director and
Chief Engineer for Propulsion
NASA/MSFC

The Problem

The high cost of space access has broad negative impacts on the U.S. space program

- Drives total satellite costs way up
- Results in loss of worldwide launch market share
- Inhibits development of new space initiatives
  - Broad civil, scientific, military, commercial, university, and research
- Prevents many new innovative small low cost satellites from ever being built
- Stifles growth in the U.S. aerospace industry
- Reduces opportunities for engineering jobs, and therefore prevents growth for future U.S. engineers

Truly low cost access to space has remained elusive for the last forty years

Something Must Change !

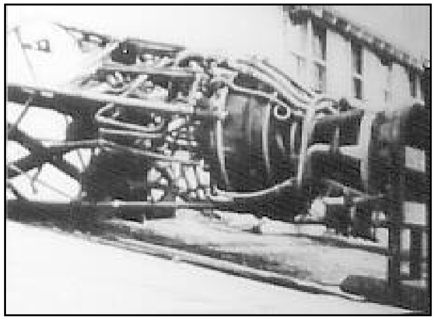
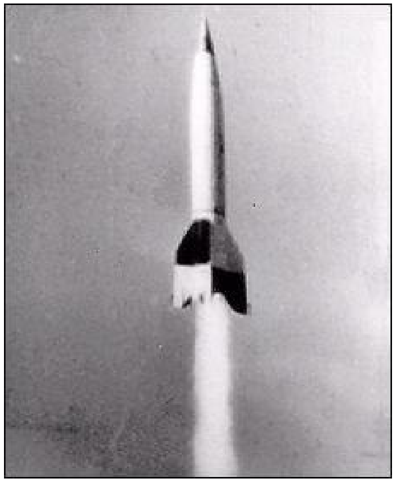
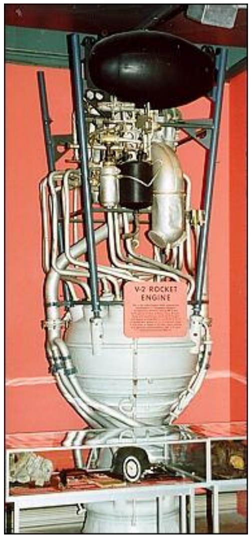
The Problem (cont'd)

- Accelerates decay of a once-powerful U.S. aerospace infrastructure
- Limits the opportunity for new aerospace companies to emerge
- Ultimately degrades the U.S. strategic position in the world, both militarily and economically
- Lack of opportunities to gain hands-on experience for U.S. industry and government engineers further degrades U.S. launch vehicle reliability
  - Recent Shuttle experiences
- Can we do anything to reverse this downward, self destructive spiral??

Yes!! We can, and that's the purpose of this discussion

Moore’s Law Analog (or lack thereof)

- While the logic density of silicon integrated circuits has doubled every 1-2 years since 1962 due to numerous innovations, how has the launch vehicle industry progressed?
- In 1944, the German V-2 missile was powered by LOX/hydrocarbon propellants delivered to the thrust chamber by two pumps driven by a steam turbine which employed hydrogen peroxide and sodium permanganate. The single stage V-2 had a ballistic throw capacity of 738 kg to a distance of about 320 km at an average price of 119600 Reichsmark (<$84k in 2003 dollars) - albeit using slave labor.
  - Rocket propulsion systems today are only modest iterations of this basic design approach. In fact, the last liquid ballistic missile (Titan II) could throw 1909 kg about 8000 km but at a unit cost of ~ $15M-$20M.
- What innovations have we leveraged in the last 60 years? - if anything, cost trending is going backwards.

The Market Today

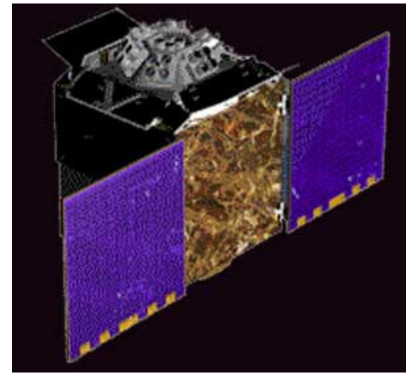
- The worldwide satellite market has been very flat
  - And is projected to stay flat for the foreseeable future
  - Around 80 plus or minus launches annually
- The mid-range worldwide launch vehicle market is over-supplied
  - Too many boosters vying to launch too few satellites
- Foreign launch vehicles have stolen the commercial market from U.S. providers
  - U.S. government payloads keep the U.S. launch market barely viable
- Available domestic small launch vehicles very limited and expensive
  - Only the government can afford to use them
  - Even the government can only afford a few
  - Flying as a secondary is usually unsatisfactory
- General commercial small satellite market very limited, because:
  - Almost no one can afford the ride
- But this market segment shows some real promise

What Is Needed

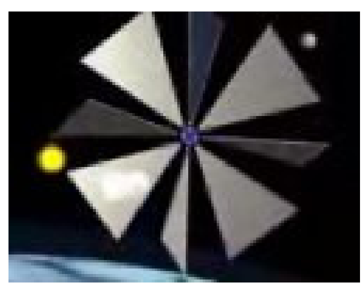
- The U.S. satellite and launch vehicle market needs a stimulus
- The small end of the market represents the best opportunity to stimulate growth
  - Lowest cost area for investment
  - Segment of the market suffering the most from high launch costs
  - Market segment that offers the easiest opportunity for start-ups/entrepreneurs
- The key is a markedly lower cost small launch vehicle
  - $5-7M recurring -- doesn't exist today
- Abundance of real data that indicates that a small launcher in this priced range will enable significant small satellite market development
  - This bootstraps more and even lower cost launchers
    - Which in turn drives an even larger more cost effective small satellite market
- Positive effects of this market stimulus will spill over to mid-range and larger boosters and satellites
- Over the long term, growth will be enabled for the U.S. aerospace industry and economy
- A new generation of U.S. engineers will get hands-on flight experience
  - Engineering job opportunities will increase
  - Engineering education will again become more attractive to many

Current Small Satellite Market Summary

Current market for small payloads is limited

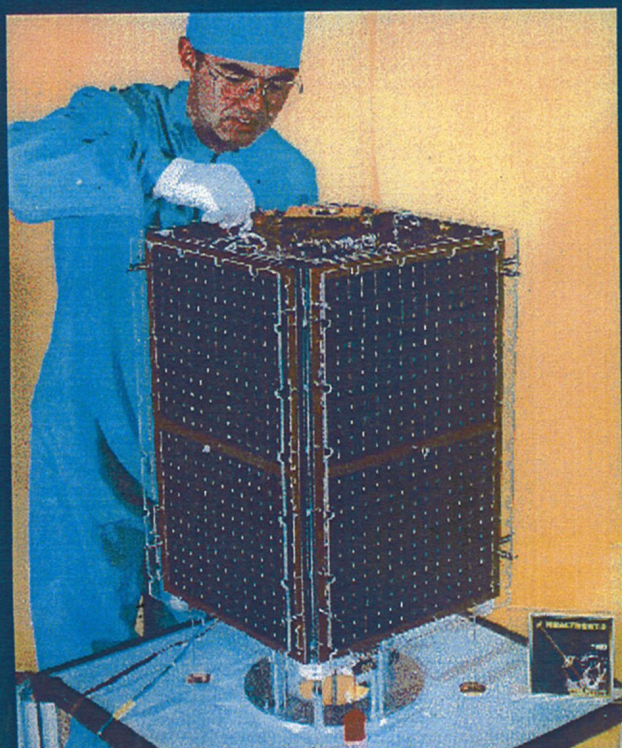


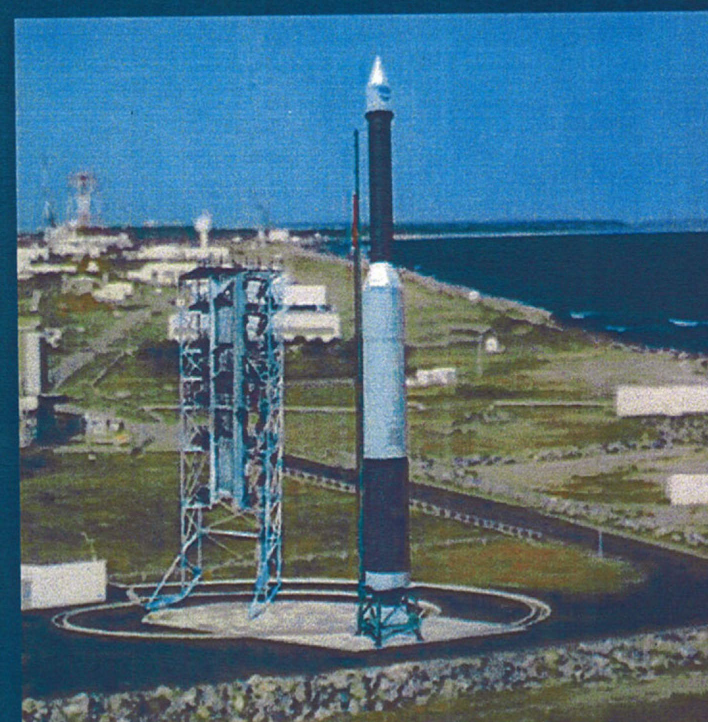
- Launches for small payloads are very expensive
  - $20M+ per dedicated launch
  - Most small satellites cost less than half the minimum launch price
- Limited sources for dedicated launch
  - Small science payloads usually cannot accept arbitrary orbit altitudes and inclinations
  - Flying as as secondary is expensive, complicated, inflexible, and uncertain
    - Large booster providers and primary payloeds have litle incentive to accommodate secondaries
- Many university/commercial small satellites never get built
  - Cost of launch makes them a non-starter
  - e.g., University of New Hampshire's CATSAT
- Foreign launch competition expanding
  - Especially from Russia
  - Planetary Society's Cosmos I
    - Launched on Russian SLBM
  - Italy's Vega



Requirement

NASA needs to provide very low cost access to orbital space for the scientific/education community through the use of standardized Microsat technologies and affordable small launchers





Definition of Small Satellites

Small Sat $\leq$ 500kg

	Class	Wet Mass
	Large Satellite	>1000kg
	Medium Sized Satellite	500-1000kg
Small Sat	Mini Satellite	100-500kg
Small Sat	Micro Satellite	10-100kg
Small Sat	Nano satellite	1-10kg
Small Sat	Pico satellite	0.1-1kg
Small Sat	Femto satellite	<100g

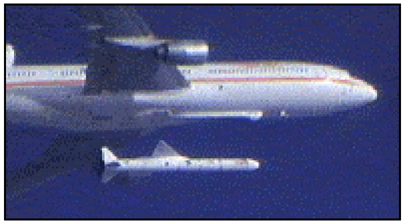
Small Sat Prices between $0.5M - $10M

Small Satellite market segments(1 to 750 kg) identified thus far that would be enhanced/enabled by ultra-low cost (< $10M) launch vehicles

Primary Market Segments

1) Military/DoD
   - Tactical
     - In-theater operations
   - Strategic
     - Decomposed ISR assets especially IR and optical (e.g. SBIR's)
     - "Three Letter" Agency "Stuff"
     - Space Asset Defense
     - Space Offense
     - HCV Boost and Beyond – Marine/Army /Special Forces Rapid Deployment
       - 30 minutes to anywhere in the world from CONUS (Anti-Terrorist)

2) Government, Civil, NASA
   - Science (μ-gravity and space vacuum environments)
   - Specific experiments in space for 6 – 12 months

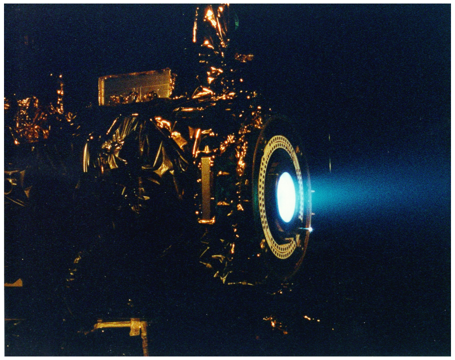


Small Satellite market segments (1 to 750 kg) identified thus far that would be enhanced/enabled by ultra-low cost (< $10M) launch vehicles (continued)

Primary Market Segments

3) Commercial
   - Experimental, e.g. single crystal growth without convection, μ-gravity.
   - Production, e.g. blades, single crystal structures, contact lens
   - Applications
     - Telecom
     - Data relay
     - Cell phone Sats
4) Pharmaceutical/Medical
   - Experimental, e.g. anti-cancer, interferon, etc.
     - Biological research
     - Radiation exposure limits
     - Genome research, etc.
5) Emergency recognition and mitigation
   - Ships/boats at sea
   - Fire monitoring (especially western USA
   - Specific/difficult to assess natural disaster monitoring
     - Tornados
     - Cat 5 "Katrina" type storms
     - Earthquakes ???

Small Satellite market segments (1 to 750 kg) identified thus far that would be enhanced/enabled by ultra-low cost (< $10M) launch vehicles (continued)



Primary Market Segments

6) Amateur users
   - Ham radio operators, OSCARS
   - Special telecom broadcast
7) Validation of new concepts/technologies in actual operating environment of space (TRL 9) for 6-12 months
   - e.g. ESSEX arcjet
   - N-Star ion thrusters
   - New sensors, etc
8) Universities
   - Unlimited – "Cube Sat" class and beyond, student designed, developed, built and operations experience
   - All ready being done, but with Russian launchers
   - "L-Prize" – Free launches for best university satellite competition winners

Small Satellite market segments (1 to 750 kg) identified thus far that would be enhanced/enabled by ultra-low cost (< $10M) launch vehicles (continued)

Future Market Segments with Potential for Growth

9) Orbital space tourism

10) Commercial orbital transportation services (COTS)

11) Rack & stack up to HLLV (a' 1a – Delta II) for CLV back-up (just-in-case)

12) Cashes for Ashes
   - e.g. Gene Roddenberry, cremation
   - Dispersion in space

Table I.2. Distribution of launched small satellites by masses

Year	Mass, kg		
	< 100	100…300	300…700
1985	12	13	3
1986	25	2	7
1987	10	12	7
1988	11	9	3
1989	13	13	2
1990	24	9	6
1991	22	18	2
1992	12	16	2
1993	10	15	1
1994	2	18	1
1995	7	3	1
1996	3	11	2
1997	9	10	52
1998	30	11	64
1999	11	5	5
2000	19	12	4
2001	11	8	3
2002	11	2	13
2003	12	8	5
2004	12	9	2
2005	4	3	5

Table I.9. The small satellites which are known to be planned for a launch up to 2010

No.	Appellation/ designation	Country	Launch mass, kg	Orbit		Number of satellites to be launched					Total
				Altitude, km	Inclination, deg.	2006	200	20 7	20 0 8	2010 0 9	
1	ABE	Brazil	200	700	89	1					1
2	AEOLUS	Europe	785	400	97		1				1
3	CBERS-4	Brazil	450	760	89	1					1
4	DESERTSAT	Egypt	200	900	90	1					1
5	EGYPTSAT 1	Egypt	100	668	98		1				1
6	EKOSAT	South Korea	180	670	98	1					1
7	GOCE	Europe	770	270	65	1					1
8	KOMPSAT 3	South Korea	700	750	99		1				1
9	MESBAH	Iran	300	800	90	1					1
10	NARSS SAT 1	Egypt	100	650	97		1				1
11	NTU X-Sat	Singapore	200	870	92	1					1
12	OSTM (JASON 2)	US/France	485	1336	66	1					1
13	PARASOL	France	115	705	98	1					1
14	RESURS-MICRO	Russia	100	510	97	1		1		1	3
15	SAOCOM-A/B-2	Argentina	500	700	92	1					1
16	SMMS	Iran	470	900	90		1				1
17	SMOS	Europe	475	757	91	1					1
18	SSR-1	Brazil	170	640	98	1					1
19	SSR-2	Brazil	250	640	98	1					1
20	SSR-3	Brazil	250	640	98		1				1
21	SSR-4	Brazil	250	640	98			1			1
22	TRSS-1	Thailand	660	507	98	1					1
23	VCL	US	433	400	67	1					1
24	VULCAN	Russia	200	500	98	1	2	1			4
In All						17	8	3	0	1	29

Proportions of the launched satellites with masses heavier than 700-800 kg in the total number of annual small satellite launches

Years	Total number of small satellite launches	Number of launched 'heavier' satellites	Share of 'heavier' satellite launches, %
1999	**26**	**5**	**19**
2000	**38**	**3**	**8**
2001	**25**	**3**	**12**
2002	**29**	**3**	**10**
2003	**31**	**6**	**19**
2004	**27**	**4**	**15**

Annual rates of the world's inventory's SLVs' launches (for injections of small satellites with launch masses no more than 700 kg) during the period of 2000-2004

SLV (country)	Quantity of annual launches					Total quantity of launches	Average annual rate of launches
	2000	2001	2002	2003	2004		
Taurus (U.S.A.)	**1**	**1**	**0**	**0**	**1**	**3**	**Less than 1**
Pegasus XL (U.S.A.)	**2**	**0**	**1**	**4**	**0**	**7**	**1.4**
Minotaur (U.S.A.)	**2**	**0**	**0**	**0**	**0**	**2**	**Less than 1**
Athena 1 (U.S.A.)	**0**	**1**	**0**	**0**	**0**	**1**	**Less than 1**
Cosmos 3M (Russia)	**2**	**0**	**2**	**3**	**1**	**8**	**1.6**
Rockot (Russia)	**1**	**0**	**2**	**1**	**0**	**4**	**1**
Dnepr 1 (Russia/Ukraine)	**1**	**0**	**1**	**0**	**1**	**3**	**Less than 1**
Start 1 (Russia)	**0**	**1**	**0**	**0**	**0**	**1**	**Less than 1**
Cyclone 3 (Russia/Ukraine)	**1**	**1**	**0**	**0**	**1**	**3**	**Less than 1**
CZ-2C/D (China)	**0**	**0**	**0**	**0**	**1**	**1**	**Less than 1**
Shavit 1 (Israel)	**0**	**0**	**1**	**0**	**1**	**2**	**Less than 1**
PSLV (India)	**0**	**1**	**0**	**0**	**0**	**1**	**Less than 1**
In all	10	5	7	8	6	36	7.2

Payload capabilities, launch prices and specific launch prices of the world's SLVs which have been rarely used or are in the process of flight testing or are planned to be put into operation in the near future

Launch vehicle (country)	LEO payload capability, *kg*	Launch price, *US$M, min/max*	Average specific launch price, *US$ K/kg*	Notes
Shtil-1 (Russia)	**150**	**1**	**6**	**Two successful launches**
Shtil-2 (Russia)	**250**	**4/5**	**18**	**Proposed improvement of Shtil-1**
Start (Russia)	**900**	**9/10**	**10.1**	**Single failed launch**
Strela-1 (Russia)	**1600**	**8/9**	**5.6**	**Single successful launch**
VLS (Brazil)	**380**	**6.5/8.5**	**19.5**	**Two failed launches**
KT-1 (Kaituozhe-1) (China)	**100**	**6.5**	**6.5**	**Two failed launches**
Angara 1.1 (Russia)	**2000**	**15/20**	**9.3**	**Would be tested by 2010**
Leolink (Israel)	**550**	**10/15**	**22.5**	**Commercial option of operation 'Shavit'**
Vega (Europe)	**2160**	**17.5/20**	**8.7**	**Tests are scheduled to 2006**

Foreign Low Cost Small Launch Vehicles Available Today

The Russian ‘Shtil-1’ SLV on a transportation carriage

The Russian ‘Start-1’ SLV in an assembling workshop

The Chinese KT-1 (‘Katuozhe-1’) SLV on a launch pad

Foreign Low Cost Small Launch Vehicles Available Today

The U.S. ‘Minotaur’ SLV before a launch

The Brazilian VLS-1 SLV at the launch site

A Proposed Stimulus

- To help develop a small launcher and small satellite market base, NASA could provide launch services at no cost to U.S. colleges and universities
  - Assumes a small launcher is available at $5-7M per launch recurring cost
  - NASA would procure and provide launch services only
    - Cost of satellite development, launch vehicle integration, and operations would be borne by educational institutions
  - Individual launches would be competitively awarded
  - Universities could compete individually or as teams
    - Single or multiple payloads on a given launch vehicle
- NASA would provide between six and ten launches per year
  - Would commit to do this for at least five consecutive years
  - Total five year budget for this initiative would be around $250M
- This initiative would kick-start the small launch market and sustain it for at least five years
  - It would also stimulate the small satellite market
- Fits with NASA's educational mandate
- Stimulates aerospace engineering programs across the country
- Engenders creative exploitation of space
- Leverages FALCON investment for low cost small launchers

SLV Operational System:

- **Small Payloads to LEO**
  - **1000 lb payload to 28.5°, circular, 100 nm altitude (baseline orbit for concept comparison)**
  - **Technologies support payload growth options**
- **Low Recurring Launch Cost (< $5M)**
- **New Launch Operations**
  - **Reach alert status within 24 hrs**
  - **Launch within 24 hrs**

Operational SLV System provides the warfighter with transformational affordable and responsive space lift capability

Phase IIa SLV Contractors

<u>AirLaunch</u>
"QuickReach"
Liquid Pressure-Fed
LOX/Propane
C-17 Launched

<u>Lockheed Martin Michoud</u>
Hybrid Pump-Fed
LOX/HTPB
Innovative CONOPS
Modular

<u>Microcosm</u>
"Eagle"
Liquid Pressure-Fed LOX/Jet-A
Common Pods - Low Cost

<u>SpaceX</u>
"Falcon I"
Liquid Pump-Fed LOX/Kerosene
High Reliability/Low Cost vs.
Maximum Performance

FALCON's Key Features

- ***Reliability(greater than or equal to 95%)***
- ***Robust design margins (low cost over performance)***
- ***Low-cost range (use of space-based range services)***
- ***Automated operational approaches***
- ***Suitable as technology test bed to retire risk for larger launchers***
- ***Scalable to low-cost mid-size and heavy lift vehicles***

Successful FALCON Outcomes

- Low-Cost SLV available for:
  - DOD
  - NASA
  - Commercial
  - Universities
  - Amateurs (OSCAR Satellites)
- Low-Cost approaches could be applied to future vehicle growth paths (10klb payload capability)

Why Will It Work This Time?

- Simplicity of Design
  - Some simple designs are inherently more reliable and lower cost than others
    - See RLS papers for last 20 years
    - NASA and DOD have really shown zero interest in inherently low costs
- Trade Design Margin Against Performance and Weight
  - Nontraditional aerospace design philosophy
  - Greater design margins enhance reliability
  - Very high Thrust-to-Weight is not that critical for low cost, vertical launch
  - Lower Thrust-to-Weight is more reliable (but vehicle T/W >1.1 @ liftoff)
- Trade Design Margin Against Redundant Systems
  - Redundancy adds complexity and cost
- Use Rack and Stack Design Approach to Achieve Component Commonality
  - Commonality enables simplicity and lowers cost
  - Commonality enhances reliability
  - Provides evolutionary design approach for heavy lift using flight-proven building blocks
- Use Commercial (non-aerospace) Processes and Components As Much as Possible
  - Leverage commercial industry's production rate
  - Commercial components are inherently higher margin; not optimized for performance
  - Commercial hardware is dramatically lower cost than comparable aerospace hardware

Small Launch Vehicle Research Project (SLVR) Strategy

- **Goal:**
  - Establish a sustainable, low cost small orbital payload capabililty to support NASA Science, Exploration and Education needs
- **Strategies:**
  - Utilize anticipated emerging low-cost ELV's
  - Leverage WFF heritage with low-cost flight projects & in-house capabilities to minimize costs
  - Use NASA partnership with DARPA to demonstrate on a Falcon demo
- **Key Principles:**
  - Develop mission elements using standards that limit mission-unique efforts
  - Accept higher risk in exchange for lower-cost & high responsiveness
  - Manage as a system, rather than as discrete elements

RLS Small Launch Vehicle Algorithm

$$\text{Cost}_{\text{SSLV}} = \frac{\text{Cost}_{\text{NR}}}{\text{Total Production}} + \left(\begin{array}{c}\text{Unit}\\ \text{Element}\\ \text{Cost}\end{array}\right)\left(\begin{array}{c}\text{Production}\\ \text{Factor}\end{array}\right)^{\rho} + \text{I}$$

where –

$\text{Cost}_{\text{SSLV}}$ = Total launch cost to SSLV customer

Cost_{NR} = Nonrecurring SSLV development costs

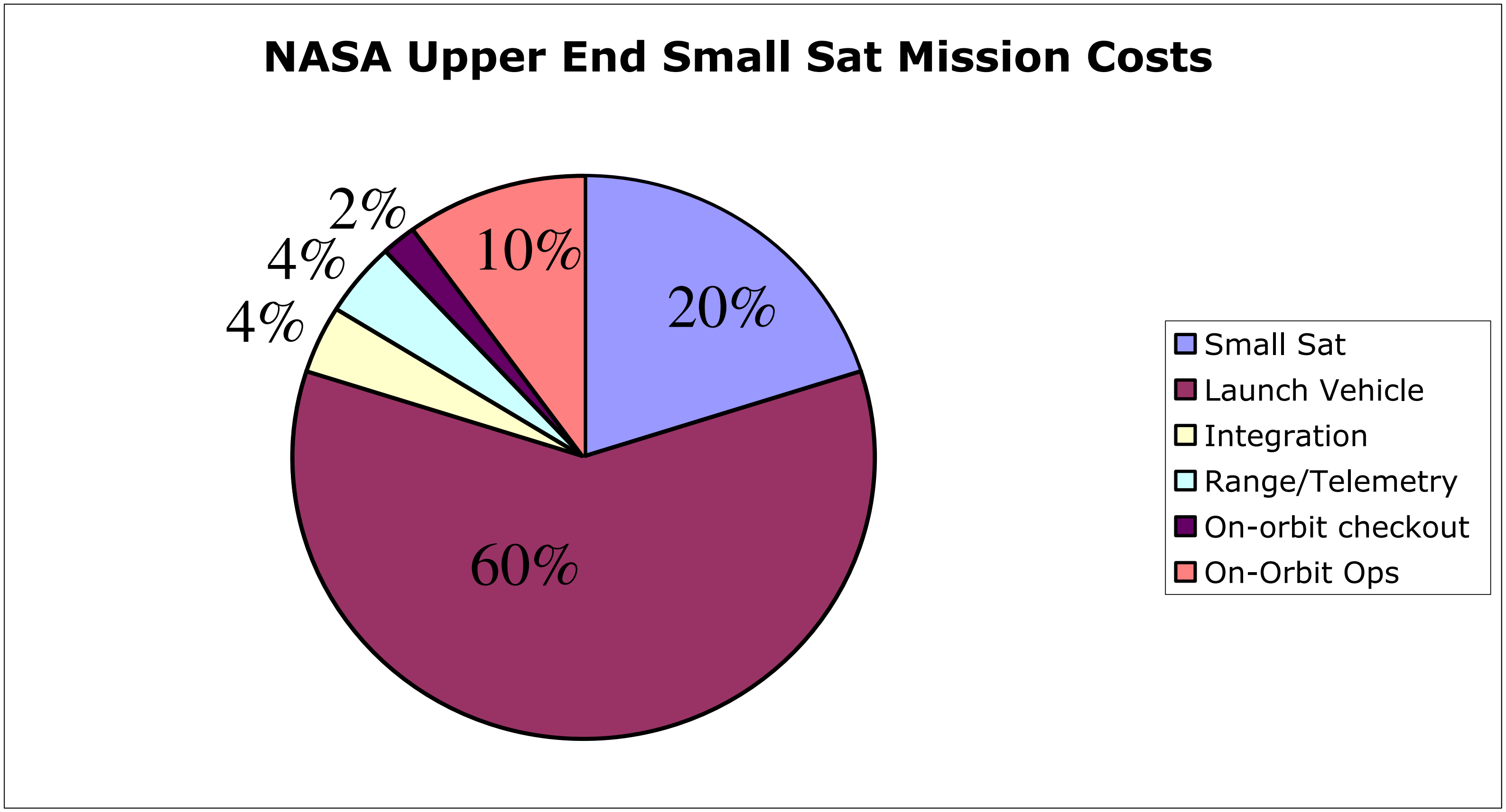
Total Production = Number of units projected over program life

Unit Element Cost = Projected single unit recurring cost

$(\text{Production Factor})^{\rho}$ = Factor to account for economies associated with volume production ($1 > \rho > 0$)

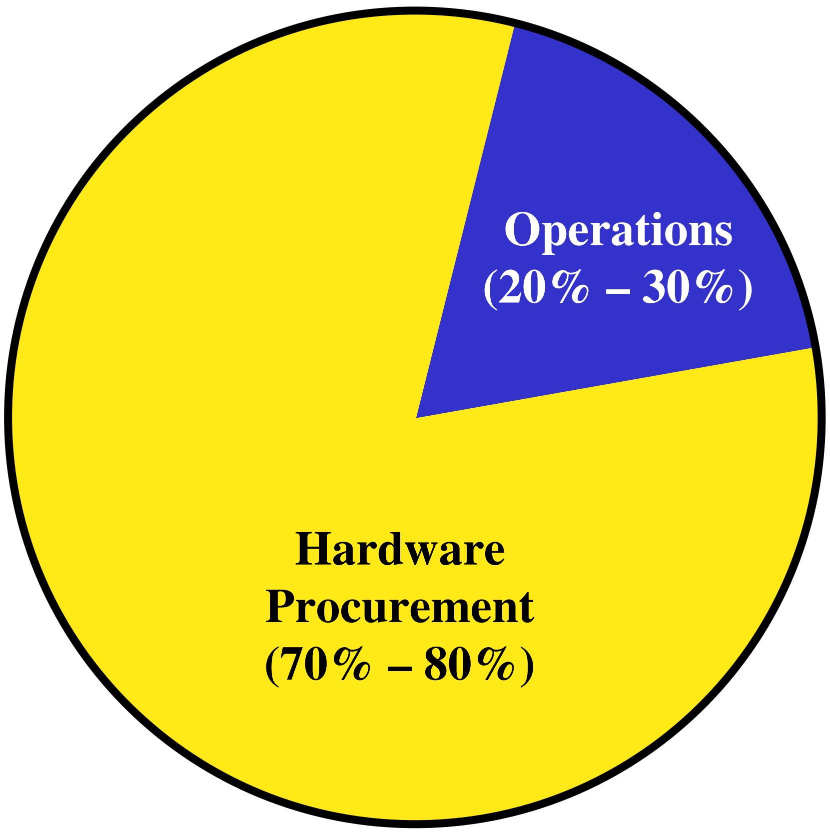
I = Variable to capture program specific costs like insurance, customization, etc

Launch Vehicle Cost Is the Primary Driver

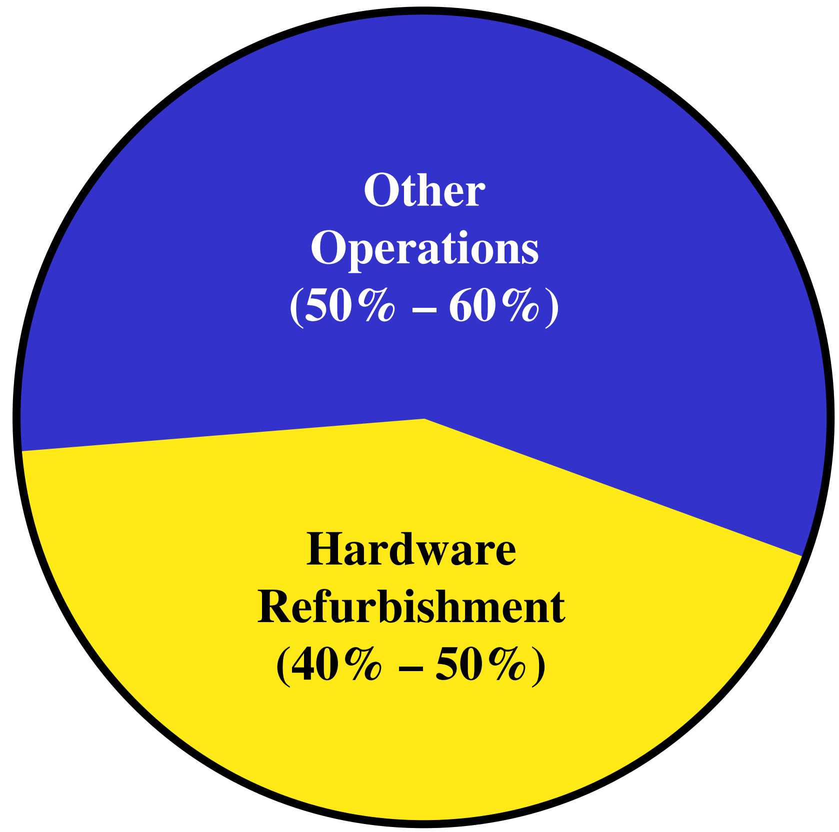


Assumptions: $10M Smallsat; $30M launch vehicle; $2M integration; $2M range/telemetry; $1M on-orbit checkout; $5M on-orbit ops

Single Mission Cost Breakdown



ELV

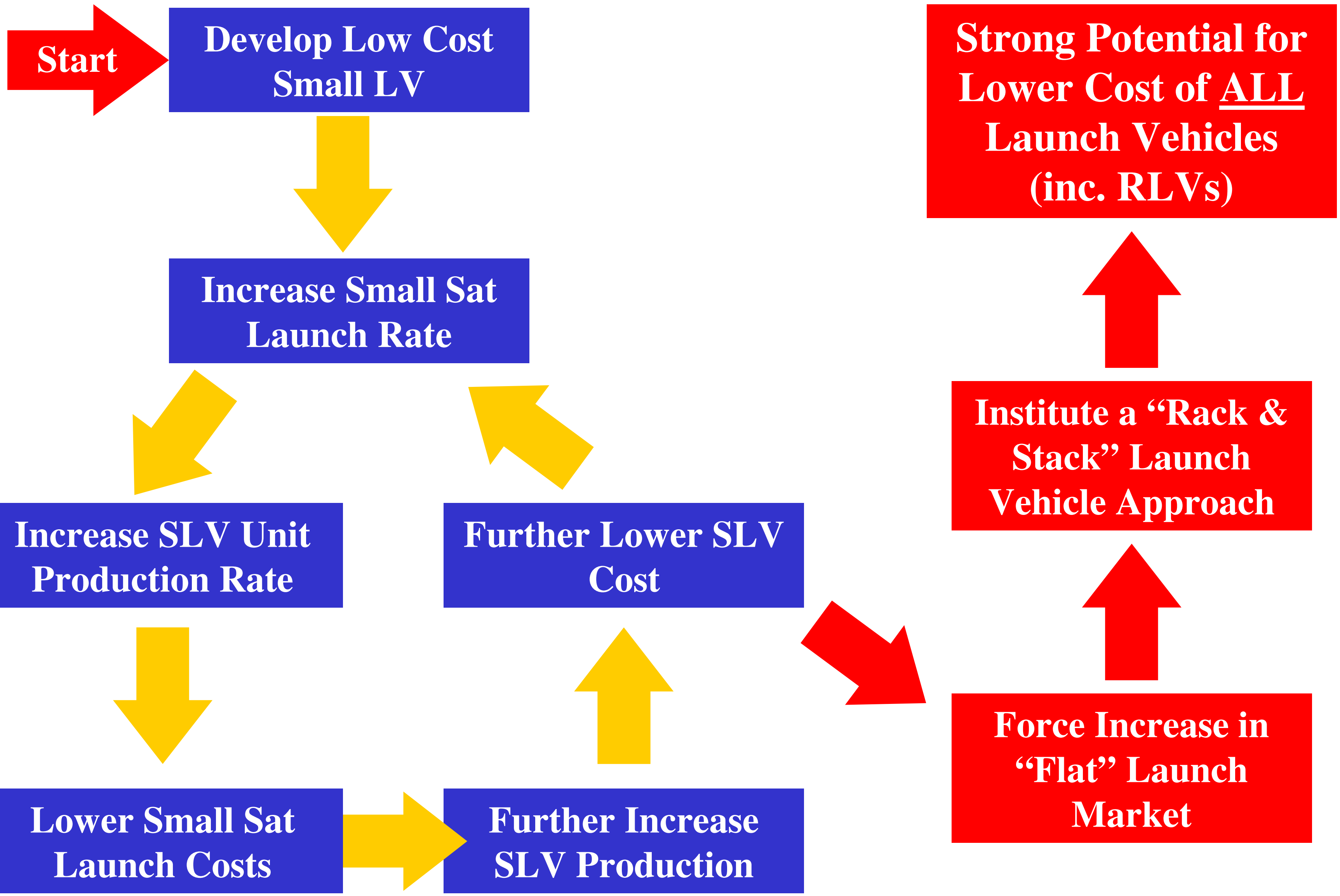


RLV (Shuttle)

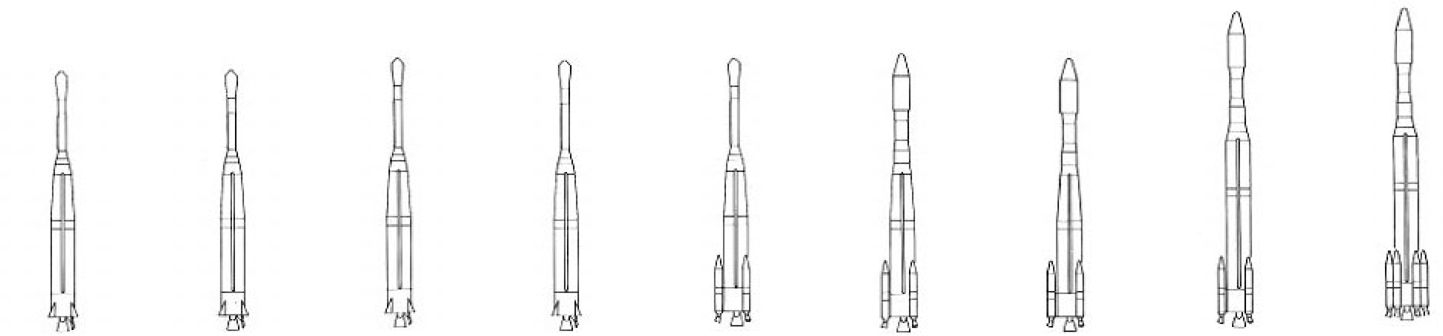
Can A Small Launcher Scale Up?

- A low cost small launcher can scale up to a low cost heavy lifter
  - Especially if this is a consideration from the beginning
- Some key technical design approaches can be taken to enable scaling
  - Highly scalable, low cost, inherently stable rocket engines
  - Commonality in manufacturing techniques and materials - from small to heavy
  - Hardware component commonality/similarity (same building blocks all the way up to heavy lift)
  - Rack and Stack building block approach
    - Modular techniques that reduce the scaling requirement of individual components
  - Commonality of non-scaling systems
    - e.g., guidance, flight software, ground software, range safety destruct
  - Common low cost automated operational approaches (like the Russians)
- Developing and flight testing common components/designs on small launcher
  - Retires a lot of the heavy lifter risk very early
  - Build and prove out elements sequentially as you scale up

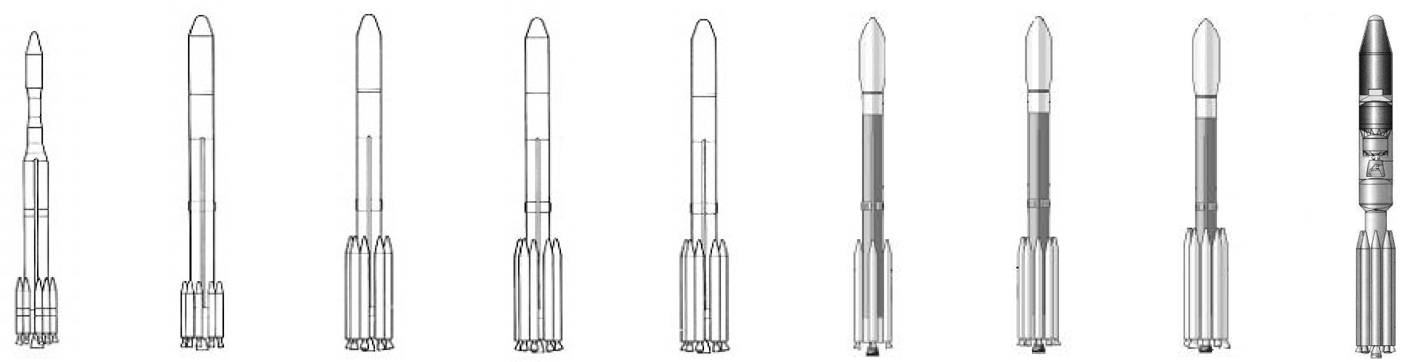
Compound Benefits of Stimulating the Small Sat/Low Cost SLV Market



Delta - A Rack and Stack Success Story



Delta	Delta A	Delta B	Delta C	Delta D	Delta E	Delta J	Delta M	Delta M 6
1960	1962	1962	1963	1964	1965	1968	1968	1968
226 kg	250 kg	370 kg	410 kg	450 kg	540 kg	947 kg	1278 kg	1634 kg
(498 lbs)	(551 lbs)	(816 lbs)	(904 lbs)	(992 lbs)	(1190 lbs)	(2087 lbs)	(2817 lbs)	(3603 lbs)



Delta 904	Delta 2914	Delta 3914	Delta 3910/PAM	Delta 3920/PAM	Delta II 7326	Delta II 7925	Delta II 7925-H	Delta III
1971	1972	1975	1980	1982	1989	1990	1990	1998
1300 kg	2000 kg	2576 kg	2935 kg	3451 kg	2731 kg	4971 kg	5815 kg	8292 kg
(2866 lbs)	(4409 lbs)	(5679 lbs)	(6470 lbs)	(7608 lbs)	(6021 lbs)	(10959 lbs)	(12820 lbs)	(18281 lbs)

Legend

7925-H	Configuration
1990	Configuration Available Date
5815 kg	Mass to LEO kg
(12820 lbs)	Mass to LEO lbs

Conclusions and Recommendations

- Overall launch market is very flat.
- Currently too expensive to fly small satellites unless flexibility and requirements allow piggybacking as a secondary payload.
- As mission costs decrease, the launch market will increase.
- As the launch market increases, the mission costs will decrease.
  - This has to be an overall stimulus (like when Japanese and Korean cars came to the U.S.A. -- Detroit said "whoops")
- A new low-cost small launch vehicle is needed to break the longstanding paradigm of small sat life cycle costs that prohibit expansion of the market.
- A highly modular rack and stack vehicle approach might be used to address larger payload needs (up to heavy lift).
- FALCON offers a unique, timely opportunity for NASA to leverage DARPA/AF funding to realize a low-cost launch vehicle which could be used by NASA and the Small Sat community within 5-6 years.
- A new small satellite launcher can be scaled to a heavy lifter at low cost, using the small launcher to retire risk
- NASA could create a tremendous stimulus by providing 6-10 launches per year to U.S. universities

BACK-Up

Table I.4. Numbers of launched ERS and scientific/experimental satellites

Year	Purpose			
	ERS	Scientific / Experimental	Communication	Navigation
1985	0	5	21	2
1986	0	4	25	5
1987	0	2	22	5
1988	1	2	14	7
1989	0	6	20	2
1990	3	8	24	4
1991	1	6	34	1
1992	2	6	20	2
1993	1	8	15	2
1994	2	6	13	0
1995	4	4	2	1
1996	0	7	8	1
1997	5	3	63	0
1998	7	6	88	4
1999	2	9	10	0
2000	3	25	7	0
2001	1	13	7	1
2002	5	10	10	0
2003	1	21	2	1
2004	4	11	8	0
2005	1	9	1	1

Annual quantities of small satellites attributed to the ‘mid-weight’ (100-300 kg) and ‘heavy’ (300-700 kg) mass categories which were launched as piggy-backs by launch vehicles of heavier classes during 2000-2004

Category of satellite	Annual quantities of launched satellite					Total quantity	Average annual quantity
	2000	**2001**	**2002**	**2003**	**2004**		
‘Mid-weight’ (100-300 kg)	**1**	**0**	**0**	**1**	**6**	**8**	**1.6**
‘Heavy’ (300-700 kg)	**0**	**2**	**0**	**0**	**0**	**2**	**Less than 1**
In all	1	2	0	1	6	10	2

U.S. Expendable Launch Vehicles- Historical Recurring Cost Breakdown (continued)

HARDWARE COST BREAKDOWN				
COST ELEMENT BY PERCENT	DELTA 7925	ATLAS CENTAUR	TITAN III	TITAN IV
STRUCTURES	24	51	41	32
AVIONICS	16	8	5	6
PROPULSION	60	41	54	60
TOTAL	100	100	100	100

TOTALS	HISTORICAL AVERAGES FOR ALL FOUR EXPENDABLE LAUNCH VEHICLES
HARDWARE AS A PERCENTAGE OF LAUNCH COST	71.25%
PROPULSION AS A PERCENTAGE OF HARDWARE COST	53.75%

U.S. Expendable Launch Vehicles- Historical Recurring Cost Breakdown

LAUNCH VEHICLE COST SUMMARY				
COST ELEMENT BY PERCENT	DELTA 7925	ATLAS CENTAUR	TITAN III	TITAN IV
HARDWARE	66	78	82	59
LAUNCH SERVICES	20	16	12	22
GOVERNMENT SUPPORT	12	6	6	19
RANGE SAFETY	2	Included above	Included above	Included above
TOTAL	100	100	100	100

Successful - Evolutionary
Rack & Stack L.V. Summary

Delta Launch Vehicle Family

- Started in 1957 as USAF IRBM that could throw 500 lbs about 200 nmi or about 500 lbs into LEO
- Evolved through 18 rack & stack iterations to the Delta II 7925H that could launch about 13,000 lbs into LEO
- Then evolved into Delta III that could launch about 20,000 lbs into LEO using same booster stage and GEM strap-ons with a very high energy upper stage (advanced Centaur-type with Isp about 446 vac)